

Concept and Beam Dynamics for a Muon Accelerator Driver (MAD) of Neutrino Factory

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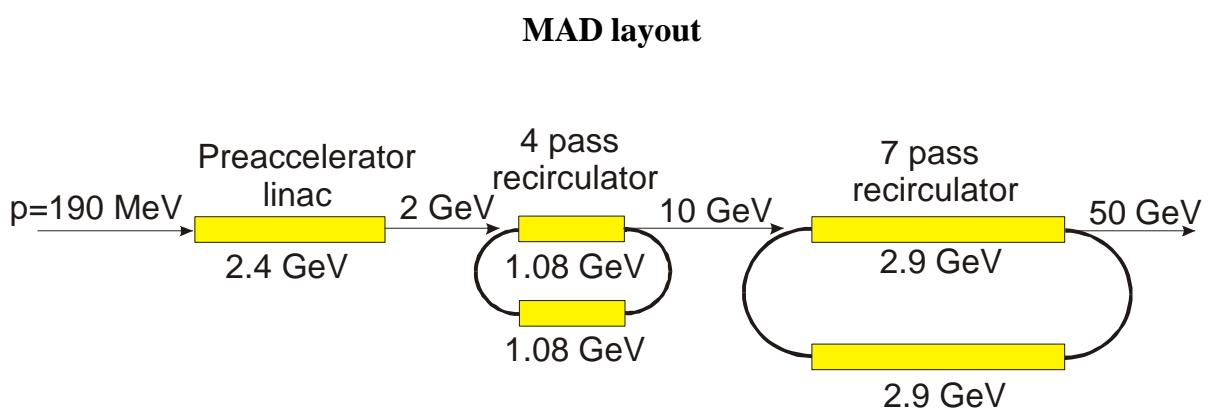
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2. Linear preaccelerator
3. First recirculator
4. Main recirculator
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Machine layout and main parameters

Basic MAD Parameters

Injection momentum/Kinetic energy	190/112 MeV
Final energy	50 GeV
Initial rms normalized emittance,	1500 mm·mrad
Initial rms energy spread	0.11
Initial rms bunch length	12 cm
Number of bunches per pulse	30
Number of particles per bunch/per pulse	$10^{11} / 3 \cdot 10^{12}$
Bunch frequency/Accelerating frequency	200/200 MHz
Repetition rate	15 Hz
Beam current in micropulse	3.2 A
Beam Power	360 kW

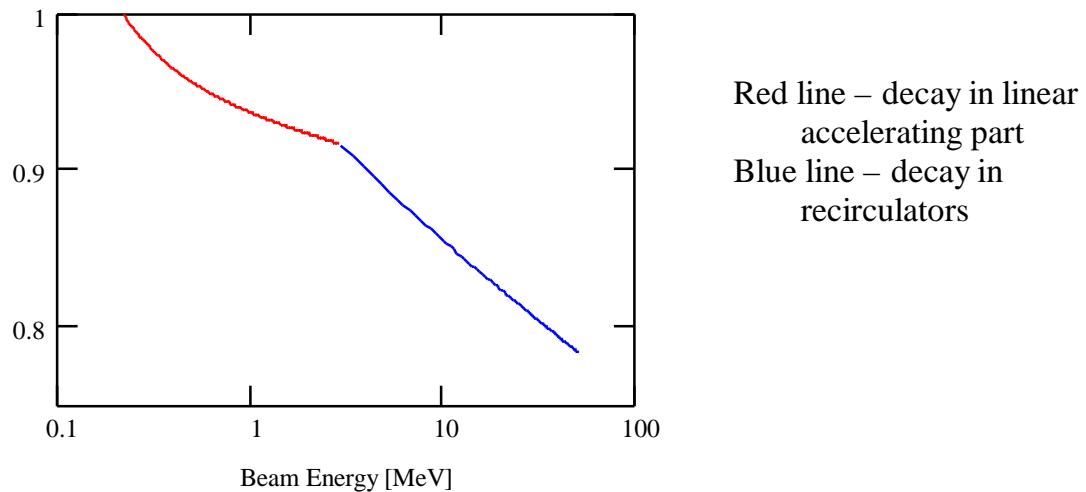


Major Points to be Addressed

- 1 Fast acceleration to prevent a decay of muons
- 2 How to capture and accelerate a huge emittance and energy spread
 - Which energy is appropriate to start recirculation
 - Number of recirculation stages
 - Accelerating frequency
- 3 Coherent beam stability

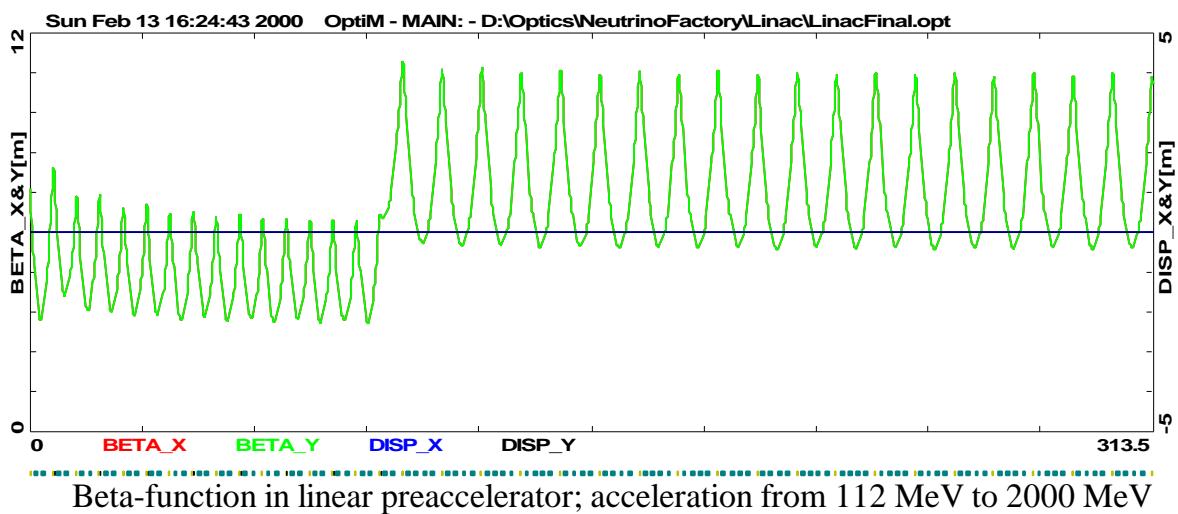
Muon Decay

- Muon decay time - 2.2 μ s
- Accelerating gradient of 15 MV/m
 - Real estate accelerating gradient in linac – 8.2 MV/m
 - Real estate accelerating gradient in recirculators – 3 MV/m
- Decay losses depends approximately linearly on the accelerating gradient



Linear Preaccelerator

- 1 Synchrotron motion in the initial part
 - suppresses effect of non-linearities in the longitudinal phase space
 - allows to perform the beam bunching
 - reduces effective accelerating gradient (2.4 GV instead 1.9 GV)
- 2 Strong transverse focusing ($b_{max} \leq 15$ m)
 - large beam size due to huge emittance
 - strong time dependent focusing in the RF cavities
 - focusing is limited by the increase of effective longitudinal mass due to transverse particle momentum ($b_{min} \geq 3$ m).
$$\left(\frac{\Delta b_{\parallel}}{b_{\parallel}} \approx -\frac{1}{2} q_{\perp}^2, \quad m_{eff} = \sqrt{m_m^2 + p^2 c^2} \right)^2$$
 - solenoidal focusing
 - Focusing element length (0.5 m) is less than its aperture (0.7 m)
- 3 Single particle tracking exhibited
 - small losses
 - small longitudinal and transverse emittance growth
- 4 Accelerator final energy is determined by
 - RF phase slip
 - Sufficiently small emittance and energy spread
- 5 RF frequency choice
 - To capture the required longitudinal phase space
 - Acceleration on the stored RF energy



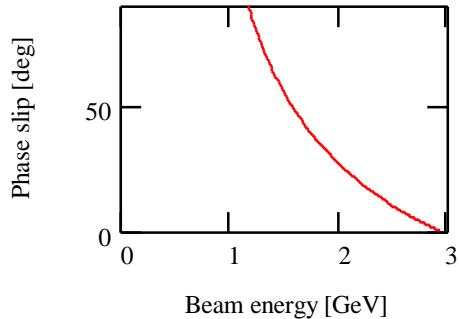
RF

15 MV/m accelerating gradient
 16 cryomodules of 5 m length
 2 two-cell cavities per cryo-module
 20 cryomodules of 10 m length
 4 two-cell cavities per cryo-module
 90 MV per cryomodule
 Maximum beam size in the cavity R=20 cm

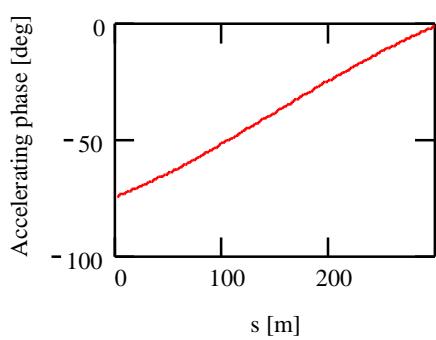
Focusing

$B_0=11$ kG (L=50 cm, $2a=40$ cm)
 $B_{10}=25$ kG (L=50 cm, $2a=32$ cm)
 $B_{18}=48$ kG (L=50 cm, $2a=28$ cm)
 $B_{19}=32$ kG (L=128 cm, $2a=28$ cm)
 $B_{27}=50$ kG (L=128 cm $2a=16$ cm)

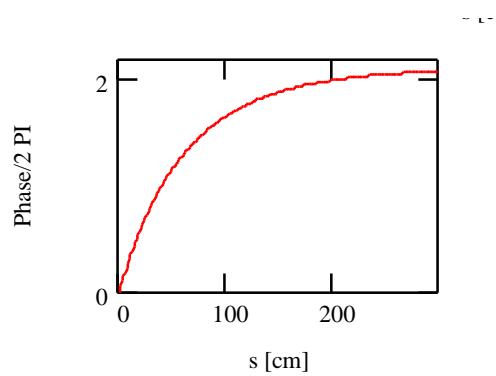
Longitudinal dynamics



Phase slip dependence on
the beam energy yields
final linac energy
to be ≥ 2 GeV



Accelerating phase along linac



Synchrotron phase along the linac

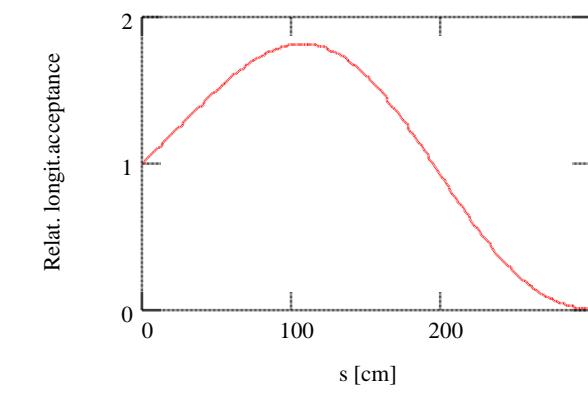
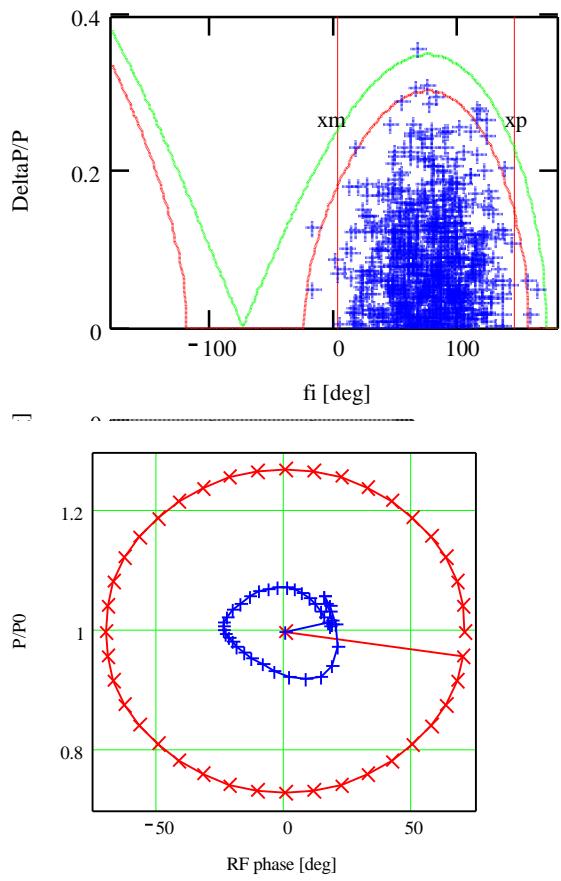
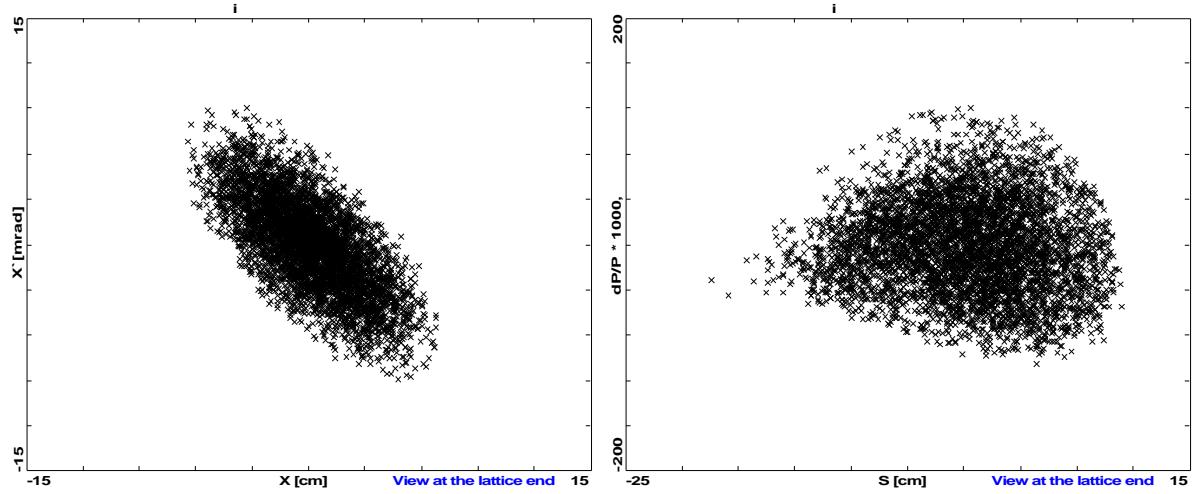


Figure 1. Separatrix size at the beginning of acceleration

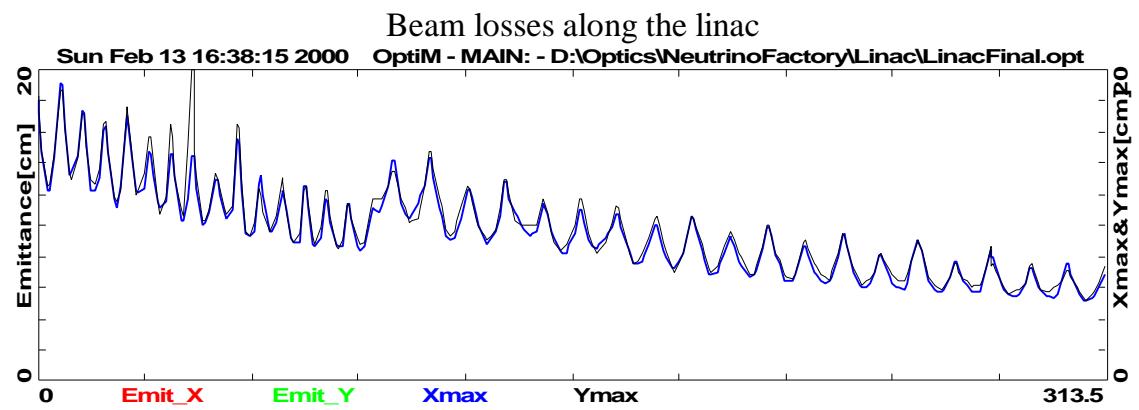
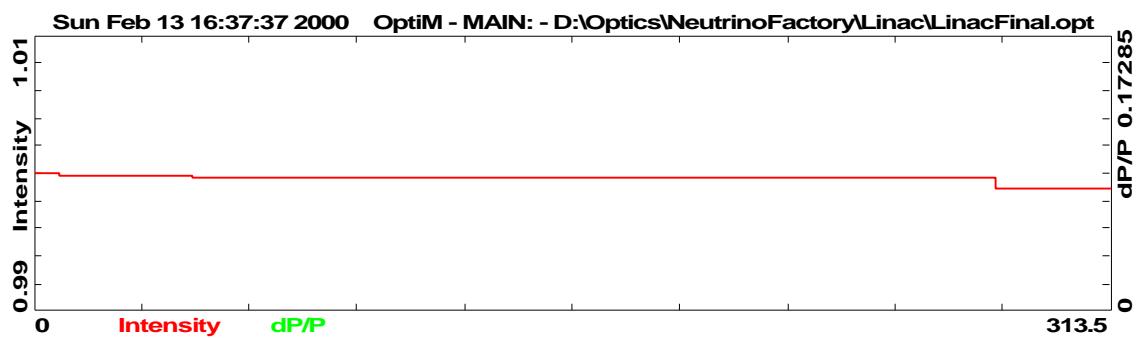
Figure 2. Relative size of longitudinal acceptance along linac

Figure 3. Phase space before and after acceleration for particles at 2.5σ (95% of particles)

Single Particle Tracking for the Linear Preaccelerator



Transverse and longitudinal phase spaces at the linac end



Rms emittance and maximum beam size (maximum particle displacement) along the linac. Rapid beam size decreases correspond to scraping of the particles with large amplitude

Tracking results for the Linear Preaccelerator

1 Initial particle distribution

➤ Gaussian distribution

- distribution truncated at 2.5σ in 6D space
 - 30% of particles are cut from the distribution
- Transverse rms emittance of $834 \text{ mm}\cdot\text{mrad}$ ($1500 \text{ mm}\cdot\text{rad}$ normalized) is converted to 540 mm mrad after truncation
- Rms bunch length - 12 cm
- Rms energy spread - 0.11

2 less than 1% of particles are lost in the course of acceleration

➤ transverse motion “instability” for of momentum particles with large amplitudes

3 No emittance growth due to scraping of the tails

➤ Final rms emittance - $55 \text{ mm}\cdot\text{mrad}$

- Linear model - $52 \text{ mm}\cdot\text{mrad}$ for not truncated distribution

➤ Final rms energy spread - 0.039

4 Output acceptance

➤ Transverse acceptance - $500 \text{ mm}\cdot\text{rad}$

➤ Energy spread - ± 0.041

First Recirculator

Beam Transport Issues

- Separation of beams for recirculation
- Beam size
 - implies need for limits on envelopes, dispersion
 - implies need for “short” cells or periods
- acceptance
 - longitudinal:
 - need momentum compaction management;
 - must be aware of nonlinear effects
 - need large momentum acceptance
 - betatron
 - need to limit momentum-driven mismatch
 - suggests need for high periodicity, aberration suppression, possible chromatic correction

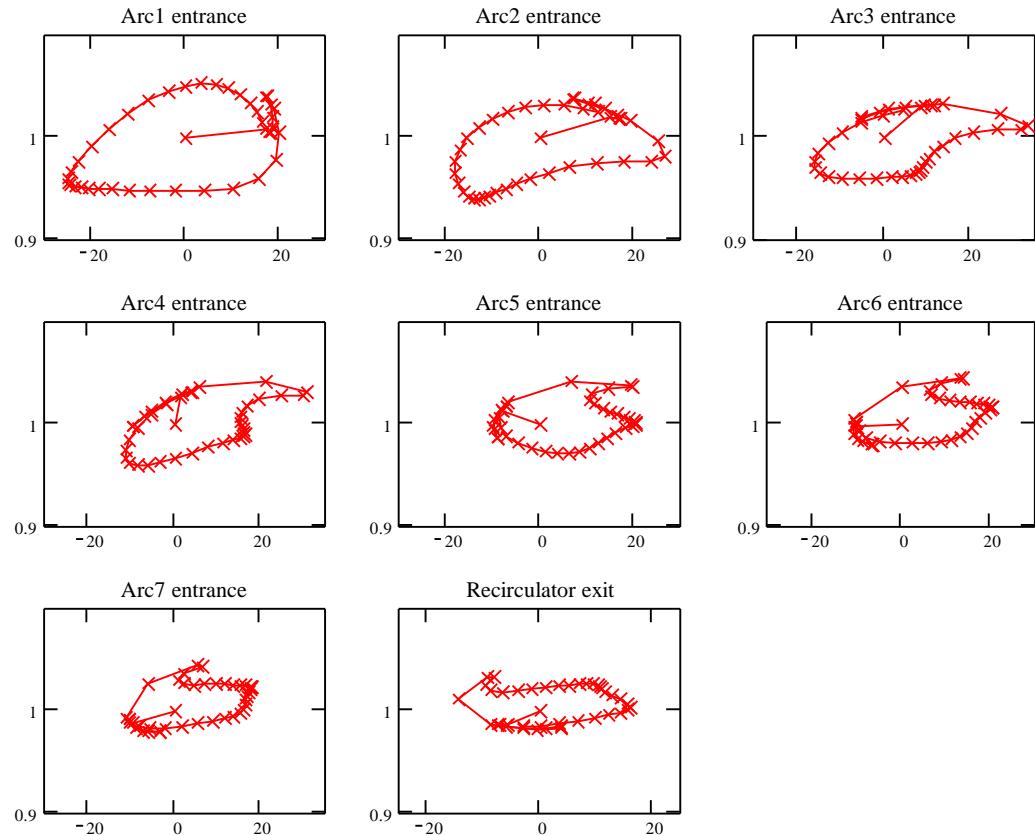
Main parameters for the first recirculator

Initial energy	2 GeV
Final energy	10 GeV
Number of passes	4
Total initial energy acceptance	$\pm 5.6\%$
Total final energy acceptance	$\pm 2.6\%$
Initial transverse acceptance	500 mm·rad
Final transverse acceptance	130 mm·rad
Emittance delusion	30%
Total voltage per linac	1.08 GV
Circumference	680 m

Main parameters for recirculation arcs and linacs

	Initial Energy [GeV]	Initial total energy acceptance	Transverse acceptance, X&Y [mm·rad]	Gang phase of the linac [deg]	M_{56} per arc [m]
	2	$\pm 5.60\%$	500	7.5	
Arc 1	3	$\pm 5.25\%$	350	18	1.1
Arc 2	4	$\pm 4.90\%$	270	28	1.4
Arc 3	5	$\pm 3.70\%$	230	28	1.0
Arc 4	6	$\pm 4.05\%$	200	22	1.5
Arc 5	7	$\pm 3.5\%$	180	28	0.7
Arc 6	8	$\pm 3.25\%$	160	22	0.7
Arc 7	9	$\pm 3.25\%$	150	18	1.4
	10	$\pm 2.60\%$	130		

Longitudinal dynamics



Arc optics

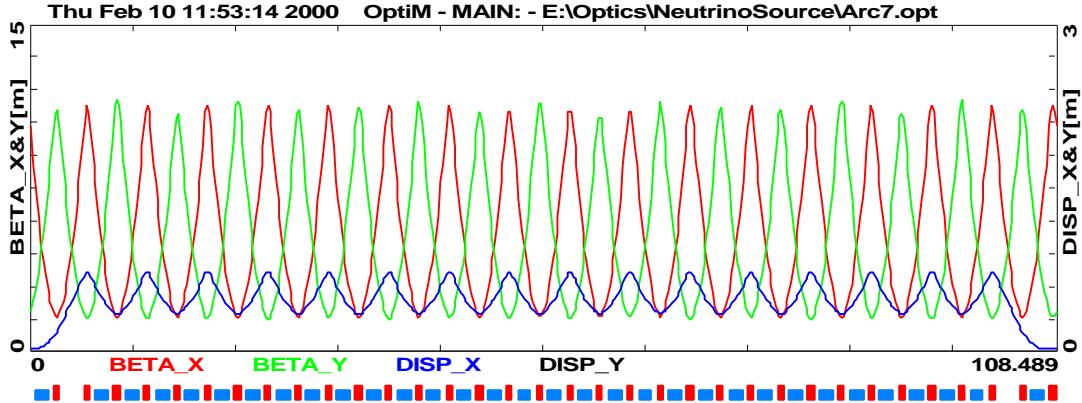
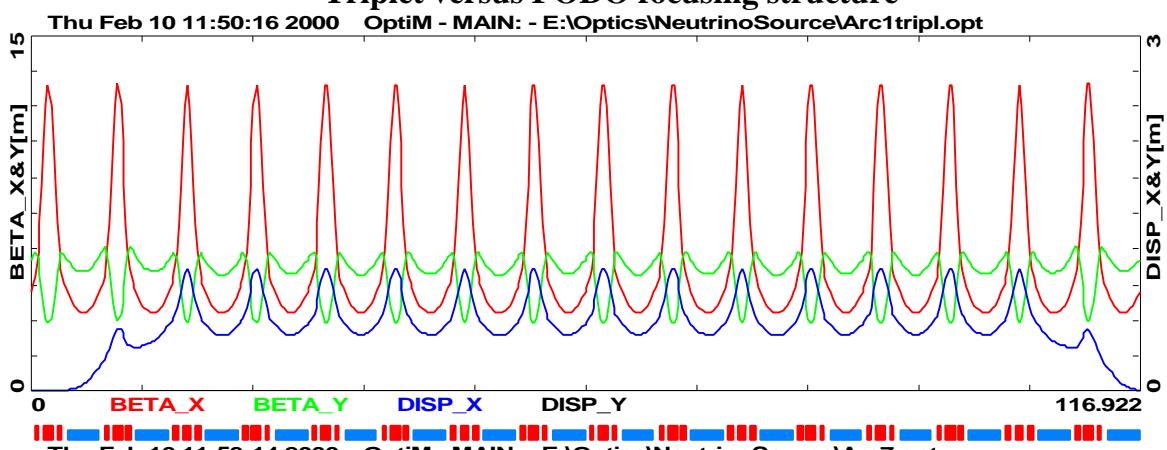
1 We know

- Large energy spread
 - High symmetry lattice to accommodate large energy spread
 - Small ratio of the beta-function to the quad focal length, β/F
- Acceptance
 - Small beta-functions
- M_{56} (~ 1 m)
- It is a recirculator not a storage ring
 - Corrected chromaticity of the beam envelopes not tunes
 - ◆ We probably do not need to use sextupoles

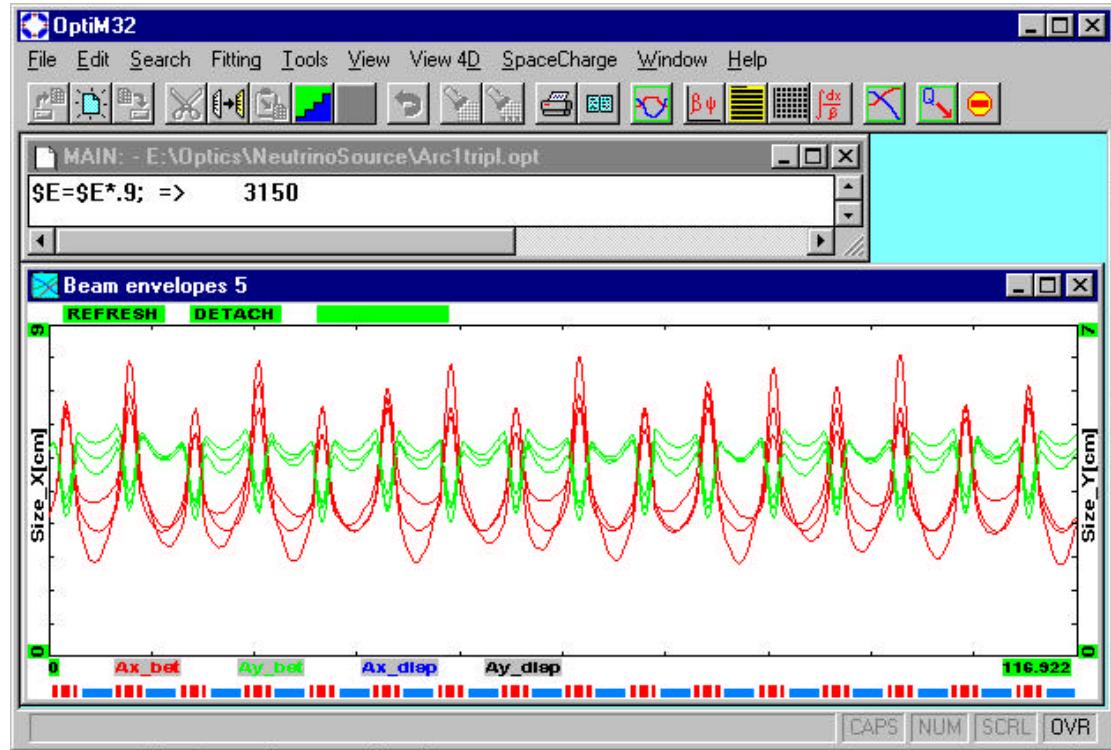
2 Focusing structure

- FODO
 - Shorter
- Triplet
 - Has smaller chromaticity for beta-functions
 - Easier to match to the solenoidal focusing in linacs

Triplet versus FODO focusing structure



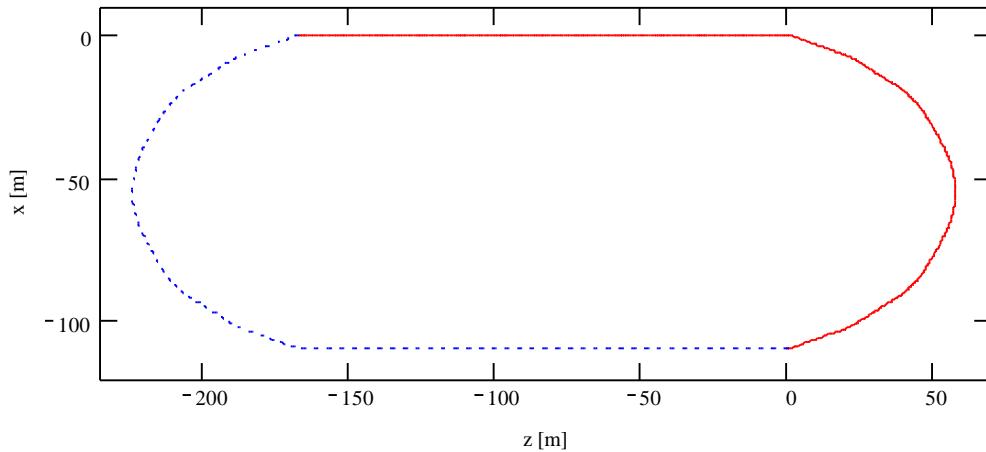
Chromaticity of the beam envelopes



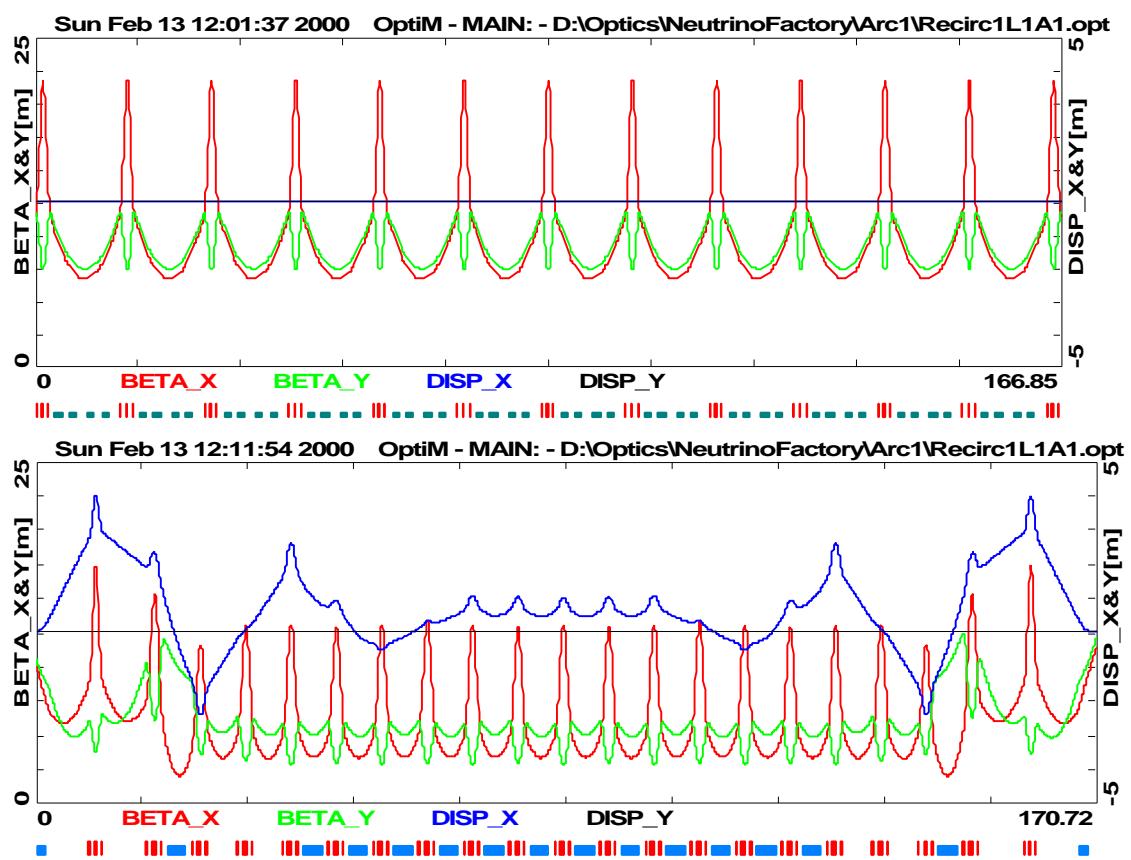
Beam envelope changes for $\pm 10\%$ energy change
CEBAF transport exhibit the same scale envelope changes for 0.1% energy change

Design choices

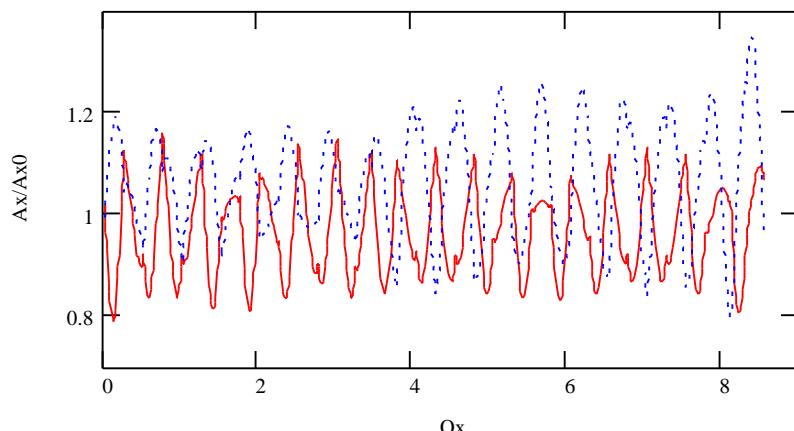
- Spreader-recombiner type
 - Single step, non-dispersion suppressed horizontal spreader/recombiner
 - Vertical spreader non-visible for given emittance and energy spread
- Multi-quad matching region
- Arcs
 - Rotationally phased 90° high-periodicity triplet focusing
 - 2 T dipoles for highest energy arc



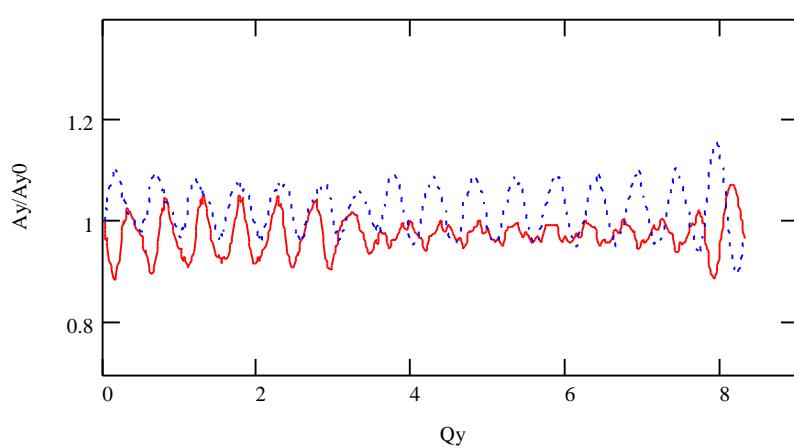
Linac 1 - Arc 1 layout



Twiss parameters for the first pass in the first linac and arc 1.



Beam envelope changes
due to momentum offset
as functions of betatron
phase advance for linac
1 and arc 1;
Red line - $\Delta p/p = +8\%$
Blue line - $\Delta p/p = -8\%$

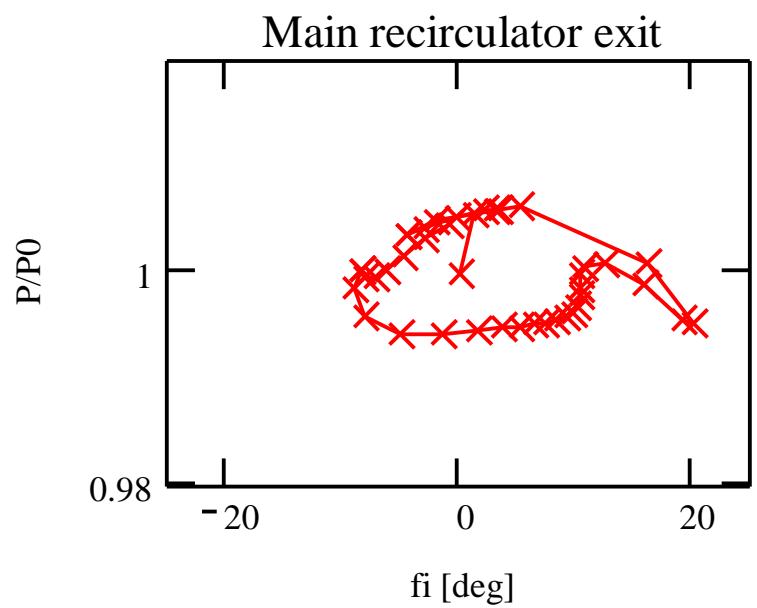


Main Recirculator

Main parameters

Initial energy	10 GeV
Final energy	50 GeV
Number of passes	7 ($\leq 7 ?$)
Total initial energy acceptance	$\pm 2.6\%$
Total final energy acceptance*	$\pm 0.6\%$
Initial transverse acceptance	130 mm·rad
Final transverse acceptance	34 mm·rad
Emittance delusion	30%
Total voltage per linac	2.9 GV
Circumference	~2-3 km

* Additional 0.5% has to be added due to beam loading effects for a train of 30 bunches.



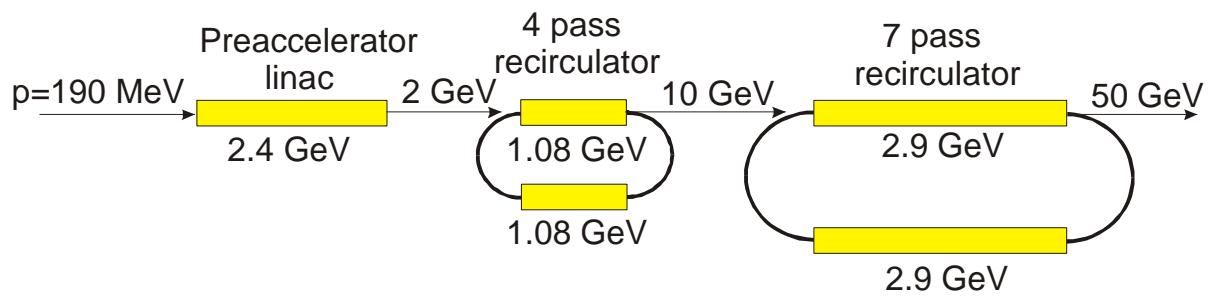
Longitudinal phase space at the main recirculator exit

Conclusion and Required R&D

- General remarks
 - There are no principal physical and technical limitations to build accelerator recirculator for muons
 - 200 MHz accelerating frequency and SC RF looks well justified
 - R&D to get 15 MV/m
 - Radiation effects on hardware (cavities, dipoles, *etc.*)
- First recirculator
 - There is no principal requirements to push dipole field beyond 2 T
 - Need concept for quad and dipoles design (high radiation)
- Second recirculator
 - Number of passes for the second recirculator

Decreasing the number of passes makes it easier but moves the cost up
 - Spreader recombiner concept (vertical is probably possible)
 - Need concept for quad and dipoles design (high radiation)
- Multi-particle effects
 - Preliminary estimates yielded that BBU should not be dangerous
 - More studies required

MAD layout



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